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ARTICLE

Soil Fertility and Crop Nutrition

Weather and soil in the US Midwest influence the effectiveness of single- and split-nitrogen applications in corn production

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Abstract

Splitting the N application into two or more timings may improve corn (*Zea mays* L.) grain yield and N recovery relative to a single-N application. A 49 site-year study across eight U.S. Midwestern states compared the effect of an at-planting (single-N application) and two split-N applications [45 (45+SD) or 90 kg N ha^{-1} (90+SD) at planting with the remainder of the total rate (180 or 270 kg N ha^{-1}) applied at V9]. For split-N applications, soil and plant responses were similar between 45+SD and 90+SD 93–98% of the time, indicating the at-planting N rate of 45 kg N ha^{-1} may be all that is needed in most cropping scenarios. Splitting the N application compared to a single-N application changed soil NO_3–N at VT and post-harvest <35% of the time and plant N uptake and grain yield <15% of the time. Split-N applications had greater grain yield in areas with uniform precipitation around the sidedress timing (Shannon Diversity Index >0.56–0.59) to incorporate N in the root zone, and in coarse-textured soil (sand content >4–10%) that had greater potential for N loss. Single-N applications produced greater grain yield in soils with more total N (>2.1–2.4 g kg^{-1}) to support N mineralization and greater cation exchange capacity (CEC) (> 27–31 cmol$_c$ kg^{-1}), silt content (>66–74%), or clay content (>24–37%) to improve nutrient and water retention. Decisions on nitrogen application timing should be made based on soil parameters and typical weather conditions around the sidedress timing.

Abbreviations: 45+SD, 45 kg ha^{-1} applied at planting and the remaining N applied at ∼V9 stage; 90+SD, 90 kg ha^{-1} applied at planting and the remaining N applied at ∼V9 stage; AWDR, abundant and well-distributed rainfall; CEC, cation exchange capacity; SDI, Shannon Diversity Index

1 | INTRODUCTION

Synchronizing N supply and N uptake of corn (*Zea mays* L.) is one strategy to optimize fertilizer-N use and reduce the risk of N loss (Dinnes et al., 2002; Gehl, Schmidt, Maddux, &

Gordon, 2005; Jones & Olson-Rutz, 2011). This strategy may work in the U.S. Midwest because farmers typically plant corn from April through May and annual precipitation is normally at its highest from March through June, which often exceeds evapotranspiration and soil water storage capacity. Further, N uptake by corn in this early season period is minimal (Abendroth, Elmore, Boyer, & Marlay, 2011). These high precipitation and low N uptake conditions lead to N fertilizer applied early in the season being susceptible to loss from denitrification or leaching (Randall, Vetsch, & Huffman, 2003a; Randall, Vetsch, & Huffman, 2003b; Randall & Vetsch, 2005; MPCA, 2013; Struffert et al., 2016). However, near the V6 corn development stage (early to mid-June) (Abendroth et al., 2011), corn begins rapid growth and takes up larger amounts of water and nutrients, which continues until approximately the R3 development stage (August). The greater uptake of water and N after V6 reduces the potential for N losses (Jokela & Randall, 1997; Randall, Vetsch, & Huffman, 2003a; Ma et al., 2003; Struffert et al., 2016). Therefore, applying a small fraction of the total N fertilizer need at planting (i.e. 20–30% of the total) and the remainder at one or more times later in the growing season is a potential strategy to increase N fertilizer use efficiency and reduce N losses.

The effectiveness of splitting up the N fertilizer application between two or more timings to improve nitrogen use efficiency and minimize N losses has been inconsistent with some studies reporting benefits and others not. For example, some studies reported split- compared to single-N applications lowered the N rate needed for optimal yield (Gehl, Schmidt, Maddux, & Gordon, 2005; Guillard, Morris, & Kopp, 1999; Randall, Vetsch, & Huffman, 2003b; Rasse, Ritchie, Peterson, Loudon, & Martin, 1999) while the amount leached from the root zone or entering tile drainage remained the same (Jaynes, 2013; Randall, Vetsch, & Huffman, 2003a). Other studies determined that yields from split- compared to single-N applications decreased or remained similar (Dellinger, Schmidt, & Beegle, 2008; Jaynes & Colvin, 2006; Jokela & Randall, 1997; Martens, Jaynes, Colvin, Kaspar, & Karlen, 2006; Randall & Schmitt, 1998), but increased the amount of N lost from the root zone to tile drainage (Jaynes & Colvin, 2006). Similarly, inconsistent results have been observed for residual soil NO_3–N after harvest where split- compared to single-N applications had less soil NO_3–N in some years, but not in others (Jaynes, 2013). Hong, Scharf, Davis, Kitchen, and Sudduth (2007) reported the amount of soil NO_3–N after harvest varied from site to site when comparing single- and split-N applications.

There are several potential reasons for the variability reported among studies evaluating single- and split-N applications. One reason may be the use of different N rates applied at each of the application timings and the timing of the sidedress applications that ranged from early corn development stages (V2–V3) to later reproductive development stages (R1–R3). Several studies also suggested the variability may be explained by soil texture (Gehl et al., 2005, 2006; Liang & MacKenzie, 1994; Spackman, Fernandez, Coulter, Kaiser, & Paiao, 2019) or precipitation (Gagnon & Ziadi, 2010; Jaynes, 2013; Randall et al., 1997; Spackman et al., 2019). However, these studies mostly compare only a few sites within a single state in the U.S. Midwest. More site-years of information is needed across a large range of soil texture and weather conditions to be able to determine at what soil property and weather information values should single- or split-N applications be used. Therefore, the objective of this study was to evaluate across a range of soil and weather conditions in the U.S. Midwest, the effect of N fertilizer timing on soil NO_3–N, plant N uptake, and corn grain yield and determine under what soil and weather conditions single- or split-N applications should be used to optimize corn production and minimize potential N loss.

Core Ideas

- Split- compared to single-N applications changed soil NO_3–N, plant N uptake, and grain yield <35% of the time.
- Split-N applications improved corn yield in coarse textured soils and areas with rainfall around sidedress.
- A single-N application at-planting improved corn yield in finer textured soils with total N of >2.1 g kg^{-1}.
- For split applications, an at-planting N rate of 45 or 90 kg ha^{-1} made little agronomic differences.

2 | MATERIALS AND METHODS

2.1 | Experimental design

Research trials were conducted at two sites (representing higher- and lower-yielding environments) in each of eight U.S. Midwestern states (Illinois, Indiana, Iowa, Minnesota, Missouri, Nebraska, North Dakota, and Wisconsin) from 2014 to 2016. Forty-nine site-years that varied in soil parameters and weather conditions were evaluated in total (Table 1). The experimental design was a randomized complete block with three N application timing treatments, two total N fertilizer rate treatments, and four replications. The three N timing treatments evaluated were a single at-planting N application (Single-N) and two split-N applications where 45 or 90 kg N ha^{-1} was applied at planting, designated as 45+SD

TABLE 1 Minimum, maximum, mean, and standard deviation of soil parameters (0–30 cm), temperature, and precipitation measurements across 49 site-years

Parameters	Min.	Max.	Mean	SD
Soil parameters[a]				
Sand, %	2	93	25	24
Silt, %	4	79	50	19
Clay, %	2	69	24	11
Bulk density, g cm^{-3}	0.9	1.9	1.4	0.1
Total C, g kg^{-1}	4	56	15	7
Total organic C, g kg^{-1}	4	48	15	7
SOM, g kg^{-1}	8	71	27	10
Total N, g kg^{-1}	0.4	4.3	1.4	0.6
C:N ratio	7	14	10	1
CEC, cmol$_c$ kg^{-1}	3	44	21	9
pH-water	5.1	8.8	6.7	0.69
Temperature				
Mean temp. (PL–V5), ˚C	14	20	17	2
Mean max temp. (PL–SD), ˚C	21	29	25	2
Mean temp. (± 10 d of SD), ˚C	19	26	22	2
Mean temp. (PL–VT), ˚C	17	22	20	1
Mean max temp. (PL–VT), ˚C	23	29	26	1
Mean temp. (PL–R6), ˚C	18	23	20	1
Mean temp. (SD–R6), ˚C	18	26	22	2
Precipitation				
Precip., sum (PL–SD), mm	68	425	214	72
SDI (PL–SD)	0.46	0.76	0.63	0.06
AWDR (PL–SD)	37	266	136	51
SDI (−30 d and +15 d of SD)	0.49	0.73	0.61	0.06
SDI (± 30 d of SD)	0.51	0.74	0.62	0.05
AWDR (± 30 d of SD)	32	316	156	58
Precip., sum (SD–VT), mm	9	208	95	52
SDI (SD–VT)	0.21	0.75	0.53	0.12
AWDR (SD–VT)	3	143	54	36
Precip., sum (± 21 d of VT), mm	25	384	151	89

[a]SOM, Soil organic matter; CEC, Cation exchange capacity; PL, planting; V5, 5-leaf vegetative development stage of corn; SD, sidedress; VT, Tasseling development stage of corn; R6, Physiological maturity development stage of corn.

and 90+SD, respectively, with the remainder of the total rate applied at the V9 ± 1 development stage (North Dakota sites in 2015 and 2016 received sidedress N between V5 and V8). The two total N application treatments were 180 and 270 kg N ha^{-1}. The 180 kg N ha^{-1} rate was chosen since it is near the average economic optimum N rate in the study region. The 270 kg N ha^{-1} rate was chosen to evaluate the influence of N application timing on corn production at a rate above what would be recommended.

Each experimental unit received N fertilizer consisting of ammonium nitrate (340 g N kg^{-1}) broadcasted on the soil surface without incorporation. Ammonium nitrate was chosen because it was expected to be suitable for surface application, provide a uniform broadcast application, allowing for soil NO_3–N and NH_4–N evaluation shortly after application, and perform more similarly across the environmental conditions in our study region (Kitchen et al., 2017). We acknowledge that ammonium nitrate is no longer a commonly used fertilizer; however, results show when different forms of N fertilizers are applied correctly, the response of corn is similar (Fernandez et al, 2009). A detailed description of experimental sites, research protocol, sampling and analytical procedures, and agronomic practices followed at all 49 site-years is provided in Kitchen et al. (2017).

2.2 | Soil sampling and analysis

A taxonomic description of the soil was completed to a depth of 120 cm within each replication at each site-year before planting. These soil cores were separated by horizons and evaluated for soil texture (percent sand, silt, and clay), bulk density, total C, total organic C, soil organic matter, total N, CEC, and pH as described in Kitchen et al. (2017). The depth of each horizon in the top 30 cm was used to calculate the weighted average for these measurements for the 0–30 cm soil depth. Soil samples (0–30 and 30–60 cm) for NO_3–N concentration at VT were obtained using a six-core (1.9 cm i.d.) composite soil sample. Post-harvest soil NO_3–N samples (0–30, 30–60 and 60–90 cm) were obtained within one to four weeks after harvest using a three-core (4.1 cm diameter core and 3.0 cm diameter tip) composite soil sample with a hydraulic sampler (Giddings Machine Company Inc., Windsor, CO, USA). Soil samples were dried (≤32 ˚C) and ground to pass through a 2-mm sieve before soil NO_3–N analysis. Nitrate-N was extracted from the soil using 0.2 mol L^{-1} KCl (Saha, Sonon, & Biswas, 2018) and measured using the Cadmium Reduction method (Gelderman & Beegle, 2012) with a modified Technicon AutoAnalyzer (SEAL Analytical, Inc., Fareham, UK).

2.3 | Plant sampling and analysis

Whole aboveground plant samples were collected from each treatment at VT and R6 (physiological maturity) by clipping six plants at ground level. For the R6 sampling, ears were removed and measured separately from the above ground vegetative matter (stover). Plant materials were dried in a forced air oven (60 ˚C) until constant mass and weighed to determine dry matter yield. Ears were shelled and dry weights of grain and cob samples were measured. Harvest grain yield was calculated from harvesting the center two rows of each experimental unit and adjusting grain weight to 155 g kg^{-1}, then adding the moisture-adjusted weight from the R6 grain samples. Nitrogen concentration of the grain and stover was measured after samples were ground to pass through a 1-mm sieve using the Dumas combustion method (Bremner, 1996) with an Elementar Rapid N Cube analyzer (Elementar Analysensyteme GmbH, Langenselbold, Germany). Whole plant, stover, grain N uptake, and grain yield were converted to mass per area (kg ha^{-1} or Mg ha^{-1}) basis using N concentration and dry biomass values as described in Sawyer, Woli, Barker, and Pantoja (2017).

2.4 | Weather measurements

Daily precipitation and minimum and maximum air temperatures were collected at each site-year with a Hobo U30 automatic weather station (Onset Computer Corporation, Bourne, MA, USA). These weather measurements were quality checked by comparing the weather station measurements against interpolated temperature data and Multi-Radar/Multi-Sensor precipitation data (The National Severe Storms Lab, NOAA). Outliers and/or missing values were replaced by the interpolated temperature or Multi-Radar/Multi-Sensor precipitation estimates (Kitchen et al., 2017). The daily temperature and precipitation measurements were used to calculate sum of precipitation, Shannon diversity index (SDI) (SDI = 1 implies complete evenness [i.e., equal amounts of precipitation in each day of the period]; SDI = 0 implies complete unevenness [i.e., all rain in one day]), abundant and well distributed rainfall (AWDR) (AWDR = sum of precipitation multiplied by SDI), and mean temperature during different time intervals as calculated in Clark et al. (2019). The irrigation water provided in eight of the experimental sites was treated as natural rainfall in the precipitation equations. Time intervals evaluated were from planting to V5, sidedress, VT, R6, and the periods in between these time points. In addition, time intervals were evaluated for 10 to 30 d before and after sidedress and VT in 5 d increments.

2.5 | Statistical analysis

All statistical analyses were completed with SAS 9.4 (SAS Institute Inc.). The MIXED procedure was used to evaluate the influence of N application timing and N rate on soil NO_3–N at VT and post-harvest, plant N uptake at VT and R6, and grain yield. Log_{10} transformations were completed for soil NO_3–N at VT and post-harvest to meet normality and constant variance assumptions. Residuals within each experimental unit of all other response variables showed normality and constant variance assumptions were met. Block within each experimental site-year was considered a random effect. The fixed effects were experimental site, N timing, total N rate, and their interactions. The influence of N application timing was evaluated at each site-year because there was a significant interaction ($P < .05$) between site-year, N timing, and N rate for each response variable (Table 2). The effect of N timing was evaluated at each N rate when the N timing × N rate interaction was significant at a site, and across N rates when there was no significant interaction. Differences due to fixed effects were determined using least square means that were calculated from LSMeans statements and adjusted for multiple comparisons when needed using Tukey's adjustment. Due to missing soil samples, evaluation of soil NO_3–N at VT was completed with 45 site-years and plant N uptake at VT with 47 site-years (2 of the 47 site-years only used the 45+SD and single-N application treatments for the comparisons).

In another analysis similar to that used in Clark et al. (2020), the MIXED procedure was used in a covariate analysis to

TABLE 2 Significance of F-values for fixed effects and their interactions and Z-values for random effects on soil NO_3–N concentration, N uptake, and grain yield across 49 site-years

Covariance parameters Fixed effects (F-value)	VT Soil NO_3–N	Post-harvest Soil NO_3–N	VT Plant N uptake	R6 Plant N uptake	Grain yield
Site	36*	31*	31*	48*	48*
N time	96*	64*	16*	9*	20*
Site × N time	3*	2*	2*	3*	5*
N rate	n/a	603*	39*	150*	20*
Site × N rate	n/a	4*	2*	2*	2*
N time × N rate	n/a	4*	1	1	0.5
Site × N time × N rate	n/a	1*	1	1*	1*
Random effects (Z-value)					
Block (Site)	0.4	2	2*	4*	5*
Residual	11*	19*	19*	19*	19*

*Significant at the .05 probability level.

determine what soil parameters and weather conditions influenced the site-year to site-year differences in the effect of N timing at each N rate on soil NO_3–N, plant N uptake, and grain yield. Soil parameters, weather conditions, N timing, N rate, and their interactions were considered fixed effects while block, site-year, and site-year by fixed-effect interactions were considered random effects. This covariate analysis was used to determine the slope and intercept coefficients for each N timing and N rate combination when regressed against soil parameters and weather conditions. Only those soil or weather variables that had a significant interaction with N application timing are shown ($P \leq .05$). When the regression lines crossed within the range of our collected data, the intersection point between 45+SD and Single-N and 90+SD and Single-N were calculated (critical value) to determine the point at which a response variable from a single-N application became greater or less than that of a split-N application (demonstrated in Figure 1).

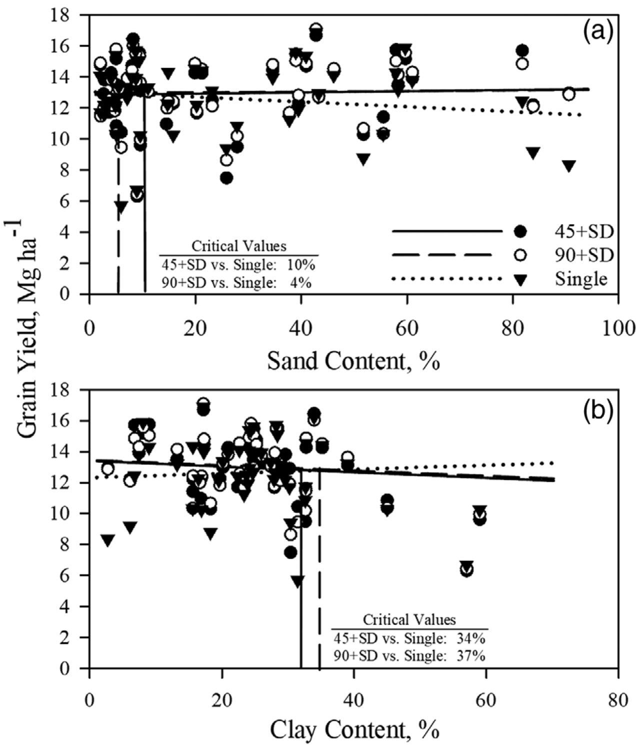

FIGURE 1 Examples of the two interpretations of critical values using the relationships between grain yield and sand (a) and clay (b) content (0–30 cm) for a single-N vs. two split-N applications (45 kg ha^{-1} at planting and remaining at ∼V9 [45+SD] or 90 kg ha^{-1} at planting and remainder at ∼V9 [90+SD]) at a total of 180 kg ha^{-1} ($P \leq .05$). a) Critical values for sand contents represents the point where smaller values were associated with greater grain yield with single-N applications and larger values were associated with greater grain yield with split-N applications. b) Critical values for clay content represent the point where smaller values were associated with greater grain yield with split-N applications and larger values were associated with greater grain yield with a single-N application

3 | RESULTS AND DISCUSSION

For split applications (45+SD and 90+SD), soil NO_3–N, plant N uptake, and grain yield were similar most of the time whether applying 45 or 90 kg ha^{-1} of the total N rate at planting regardless of total N rate applied (180 or 270 kg N ha^{-1}). Specifically, soil NO_3–N at VT and post-harvest was not affected by the at-planting N application rate 98% of the time (Figure 2a; Supplemental Table S1) and plant N uptake at VT and R6 along with grain yield 93 to 98% of the time (Figure 2b; Supplemental Table S2). These results demonstrate that the amount of N applied at planting (45 or 90 kg ha^{-1}) and sidedress when splitting N applications minimally affected differences in soil NO_3–N, plant N uptake, and grain

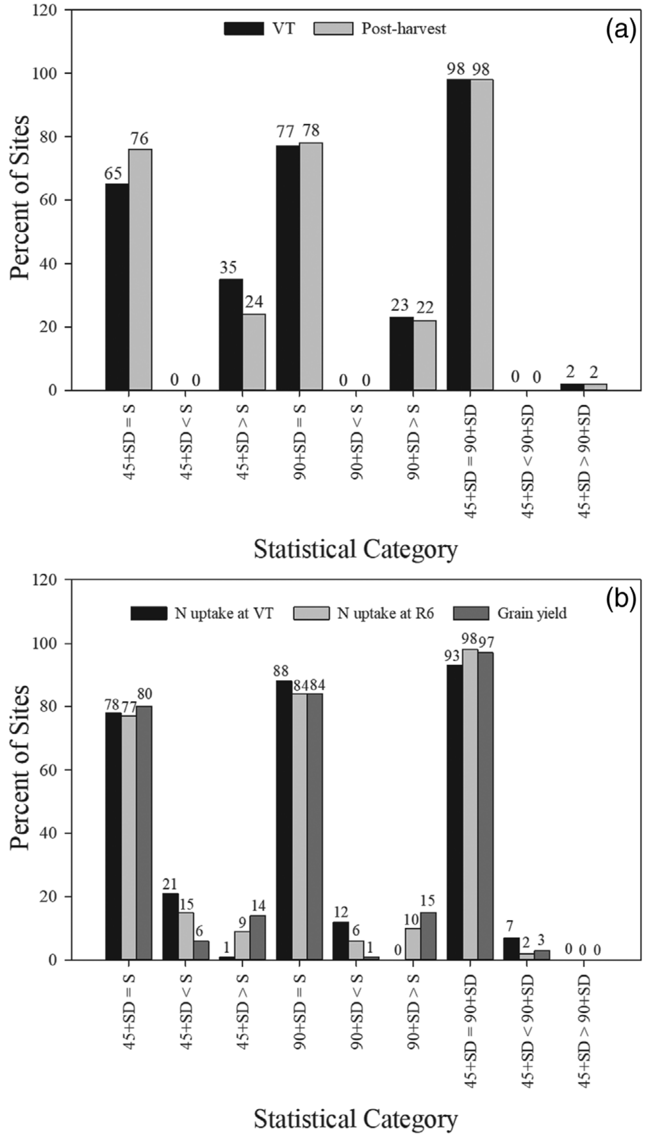

FIGURE 2 Statistical categories comparing the percent of sites with similarities and differences in a) soil NO_3–N concentration at VT (0–60 cm) and post-harvest (0–90 cm), and b) plant N uptake at VT and R6 and grain yield among three N application timings (single-N application at planting [S] and two split applications with 45 [45+SD] or 90 kg ha^{-1} [90+SD] at planting and the remainder applied at ∼V9) across 45 and 49 site-years for VT and post-harvest soil NO_3–N, respectively. Comparisons for soil NO_3–N at VT were made at the 180 kg N ha^{-1} rate only; post-harvest soil NO_3–N included both 180 and 270 kg N ha^{-1} rates

yield. Therefore, either at-planting N rate strategy could be used to optimize these variables.

3.1 | Soil NO_3–N at VT and post-harvest

Splitting the N application compared to a single-N application changed soil NO_3–N at VT and post-harvest ≤35% of the time. (Figure 2a; Supplemental Table S1). When N application timing affected soil NO_3–N, the single-N application always had less soil NO_3–N at VT and post-harvest than one or both split-N application treatments. Specifically, soil NO_3–N at VT and post-harvest with a single-N application were less than 45+SD split 24 to 35% of the time (2.2 to 46.4 mg kg^{-1} more with a mean of 9.7 mg kg^{-1}) and less than 90+SD split 22 to 23% of the time (2.6 to 19.2 mg kg^{-1} more with a mean of 7.0 mg kg^{-1}). Even increasing the total N rate from 180 to 270 kg N ha^{-1} rarely changed the effect of N timing on soil NO_3–N at VT and post-harvest. In the three site-years where N rate affected N timing, there were no differences in soil NO_3–N at the 180 kg N ha^{-1} rate, but at the 270 kg N ha^{-1} rate, there was more soil NO_3–N with split-N applications compared to a single-N application. Thus, single or split applying N fertilizer most often resulted in similar amounts of NO_3–N in the soil for the crop to take up at VT or remaining in the soil after the growing season that was susceptible to loss from the root zone. The sum and evenness of precipitation and temperature did, however, influence the effect of N timing on soil NO_3–N at VT (Figure 3) and post-harvest (Figure 4).

Soil NO_3–N at VT and post-harvest was greater with split- compared to single-N applications in site-years with greater total precipitation and evenness of precipitation (greater SDI) from planting to sidedress and less precipitation after sidedress N application (Figures 3a–d and 4a–f). This result likely occurred because higher precipitation before sidedress and less after resulted in the single-N application being disproportionately more susceptible to N loss conditions than the split-N application. However, soil NO_3–N at VT and post-harvest from single- and split-N applications became similar in site-years where total precipitation and evenness of precipitation (AWDR and SDI) was least from planting to sidedress and greatest after sidedress N application (Figures 3a–d and 4a–f). This likely occurred because less precipitation before sidedress N application minimized loss of N fertilizer applied at planting, while greater precipitation after sidedress N application resulted in similar losses of both at-planting and sidedress N applications.

The mean and mean maximum temperature during the growing season also influenced the effect single- and split-N applications had on soil NO_3–N at VT and post-harvest (Figures 3 and 4). Split-N applications generally had greater soil NO_3–N at VT than the single-N application in site-years where the lowest mean maximum temperatures from planting to sidedress or VT (Figure 3e–f) or the lowest mean temperature from the 10-d period before and after sidedress N application occurred (Figure 3g). The split-N applications also generally had greater post-harvest soil NO_3–N relative to single-N application at site-years with the lowest mean temperatures between sidedress N application and corn maturity (R6) (Figure 4g). Lower temperatures before and around sidedress N application likely resulted in less evapotranspiration by the

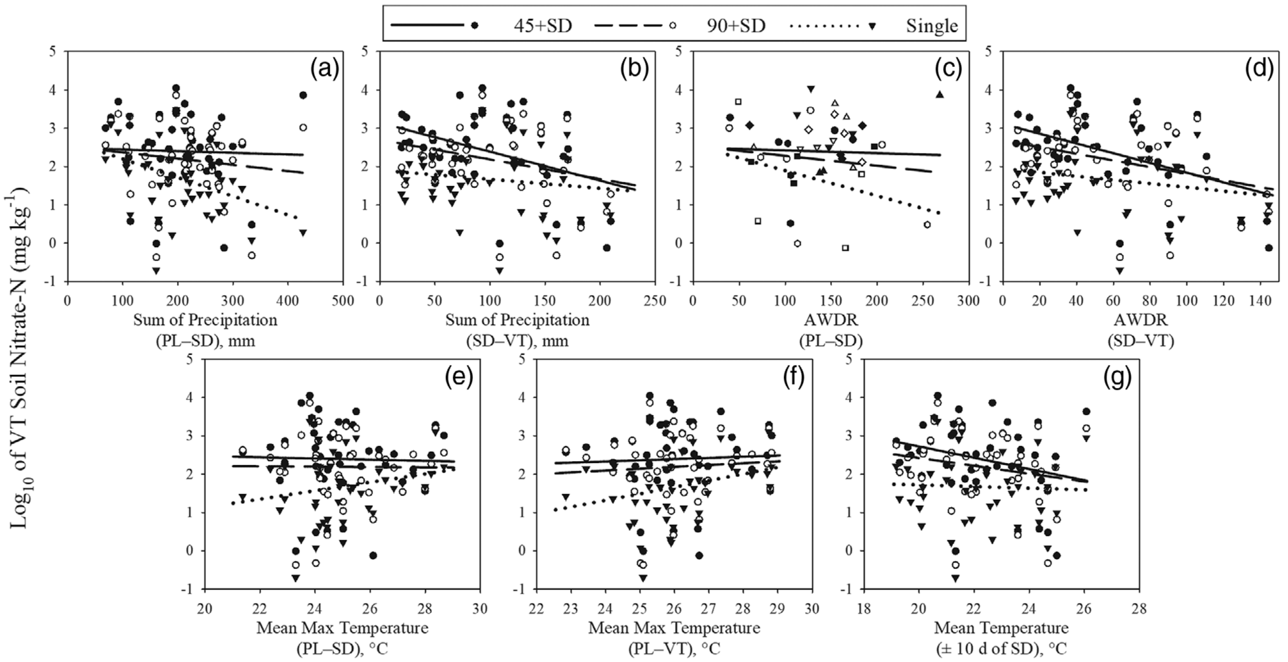

FIGURE 3 Soil NO_3–N (0–60 cm) at VT as a function of the sum of precipitation (a, b), abundant and well-distributed rainfall (AWDR) (c, d), and mean temperatures (e, f, g) from planting (PL) to sidedress (SD) or VT, SD to VT, or 10 d before and after SD of a single- and two split-N applications (45 kg ha^{-1} at planting and remainder at ∼V9 [45+SD] or 90 kg ha^{-1} at planting and remainder at ∼V9 [90+SD]) at a total of 180 kg ha^{-1} across 45 site-years. Only soil or weather variables that had a significant interaction with N application timing are shown ($P \leq .05$). R-square values were ≤0.19

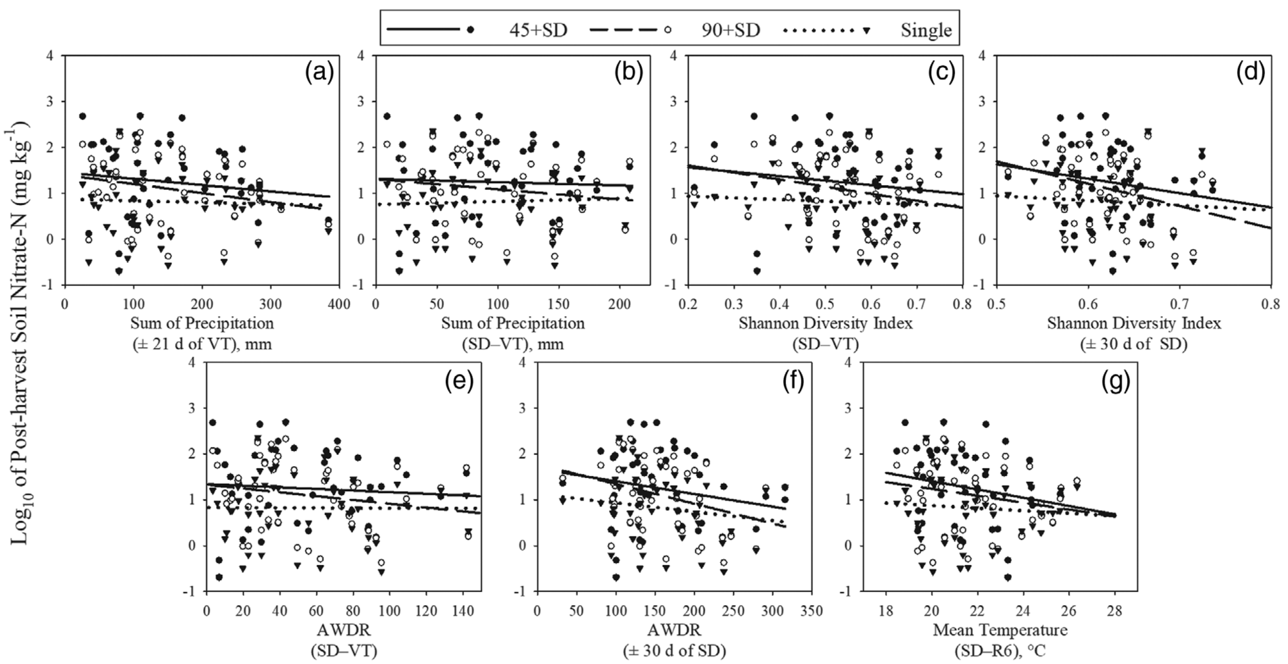

FIGURE 4 Post-harvest soil NO_3-N (0–90 cm) as a function of the sum of precipitation (a, b), Shannon Diversity Index (c, d), Abundant and Well-Distributed Rainfall (AWDR) (e, f) and mean temperature (g) from sidedress (SD) to VT or R6 or 21–30 d before and after SD or VT of a single- and two split-N applications (45 kg ha^{-1} at planting and remainder at ∼V9 [45+SD] or 90 kg ha^{-1} at planting and remainder at ∼V9 [90+SD]) across two N rates (180 and 270 kg ha^{-1}) and 49 site-years. Only soil or weather variables that had a significant interaction with N application timing are shown ($P \leq .05$). R-square values were ≤0.06

crop, increasing the potential for NO_3–N applied at planting to be lost (leaching or denitrification) from the root zone. Conversely, soil NO_3–N at VT and post-harvest from single- and split-N applications became similar as the mean maximum and mean temperature during the growing season increased (Figure 3 e–g and 4g). Higher temperatures before and around sidedress application would lead to greater evapotranspiration and less potential for NO_3–N loss, resulting in fewer differences in soil NO_3–N due to N application timing. Other studies reported similar effects of N application timing on soil NO_3–N due to the influence of precipitation and temperature (Gagnon & Ziadi, 2010; Gehl et al., 2005, 2006; Jaynes, 2013; Liang & MacKenzie, 1994). The strength of the relationships between soil NO_3–N from each N application timing treatment and weather conditions were significant ($P \leq .05$) but not strong ($R^2 \leq 0.19$). However, these relationships are important because they helped explain in part how weather conditions influenced the effect of N application timing on soil NO_3–N.

These results indicate that the effect of N application timing on soil NO_3–N content is likely more strongly influenced by N loss caused by weather conditions throughout the growing season than N uptake of the crop. Even in those sites where plant N uptake was greater in single- or split-N applications, post-harvest soil NO_3–N was lessened in only one of the 49 site-years (Supplemental Table S2). Further, this study indicates that the effectiveness of split- relative to single-N applications in improving N use and reducing N loss would be better determined by N uptake of the crop, grain yield, or other methods, and not simply by post-harvest soil NO_3–N.

3.2 | Plant N uptake at VT and R6

Splitting the N application compared to a single-N application changed plant N uptake at VT and R6 ≤21% of the time. (Figure 2b; Supplemental Table S2). Plant N uptake with a single-N application was greater than the 45+SD split 15 to 21% of the time (18 to 88 kg ha^{-1} more with a mean of 35 kg ha^{-1}), greater than the 90+SD split 6 to 12% of the time (16 to 69 kg ha^{-1} more with a mean of 24 kg ha^{-1}), and was less than either split 1 to 9% of the time (20 to 65 kg ha^{-1} less with a mean of 51 kg ha^{-1}). Even though split-N application resulted in similar or greater NO_3–N in the soil at VT compared to single-N application (Figure 2a), this greater availability of soil NO_3–N rarely led to greater plant N uptake by the VT or R6 development stage (Figure 2b). Further, increasing the total N rate from 180 to 270 kg N ha^{-1} rarely changed the effect of N timing on plant N uptake at VT and R6. In the two site-years where N rate affected N timing, increasing the N rate increased the N uptake of the single-N application to be similar to the two split applications in one site-year and greater in the other site-year. Soil and weather conditions did, however, influence the effect of N timing on plant N uptake at VT (Figure 5) and R6 (Table 3).

Plant N uptake at VT and R6 was greater with single- compared to split-N applications in finer textured soils (greater silt and clay but less sand content), at higher CEC, or with higher temperatures from planting to VT or R6 (Figures 5a–d; Table 3). In addition, plant N uptake at R6 was greater with single- compared to split-N applications in soils with greater total N or C:N ratio and less even rainfall before and after sidedress timing (Table 3). A single-N application likely does well in these soils and weather conditions because they normally have a greater capacity to retain water and nutrients for the crops throughout the growing season than low CEC, total N, and coarse-textured soils, regardless of N application timing (Saxton & Rawls, 2006; Vinten, Vivian, Wright, & Howard, 1994). Similar findings have been reported (Gehl, Schmidt, Godsey, Maddux, & Gordon, 2006; Liang & MacKenzie, 1994). Conversely, plant N uptake at VT and R6 was greater with split- compared to the single-N application in coarser textured soils (greater sand and less silt and clay content) or as evenness of precipitation before and after sidedress increased (higher SDI) (Figure 5f; Table 3). In addition, plant N uptake at R6 was greater with split- compared to single-N applications in soils with lower CEC, total N, C:N ratio, and cooler temperatures between planting and R6 (Table 3).

TABLE 3 Critical soil or weather values above which greater plant N uptake at R6 was observed for a single-N application (A) or split-N applications (B). Only soil or weather variables that had a significant interaction with N application timing are shown ($P \leq .05$)

Variable[a]	Critical value 45+SD[b] vs Single	90+SD[c] vs Single	F-value
(A)			
Silt, %	49	67	6.2
CEC, cmol$_c$ kg^{-1}	19	30	4.9
Total C, g kg^{-1}	16	21	3.7
Total organic C, g kg^{-1}	14	21	3.4
SOM, g kg^{-1}	25	37	4.4
Total N, g kg^{-1}	1.3	2.0	4.5
C:N ratio	11:1	9:1–13:1[d]	4.1
Mean temp. (PL–R6), ˚C	19–20	18–21	4.1
Mean temp. (SD–R6), ˚C	20–21	19–23	4.7
(B)			
Sand, %	27	6	7.6
SDI (−15 +30 d of SD)	0.63	0.57	3.4

[a]SOM, Soil organic matter; CEC, Cation exchange capacity; PL, planting; R6, Physiological maturity development stage of corn; SD, sidedress.
[b]45 kg N ha^{-1} at planting and remaining at ∼V9.
[c]90 kg N ha^{-1} at planting and remainder at ∼V9.
[d]The N time by N rate interaction was significant and the critical value for both N rates falls within the given range.

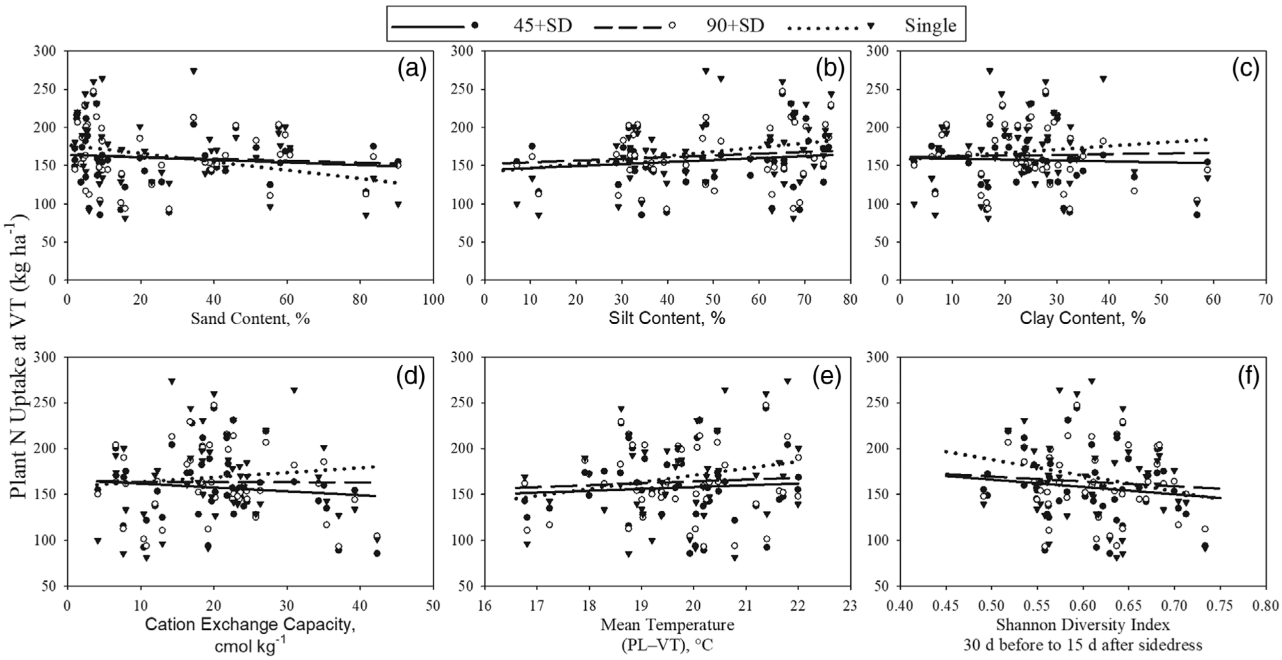

FIGURE 5 Plant N uptake at VT as a function of soil (a, b, c, d) and weather conditions (e, f) from planting (PL) to VT (e) and 30 d before and 15 d after sidedress N application of a single- and two split-N applications (45 kg ha^{-1} at planting and remaining at ~V9 [45+SD] or 90 kg ha^{-1} at planting and remainder at ~V9 [90+SD]) across two N rates (180 and 270 kg ha^{-1}) and 47 site-years. Only soil or weather variables that had a significant interaction with N application timing are shown ($P \leq .05$). R-square values were ≤0.14

Split-N applications likely do well in these soils and weather conditions because of their greater susceptibility for N loss during the high precipitation and low N uptake period early in the season compared to finer textured soils with greater CEC. Greater evenness in precipitation before and after the sidedress timing likely increased N availability by incorporating the fertilizer into the root zone.

Plant N uptake at VT from single- and split-N applications became similar as sand, silt, and clay content along with CEC, or early season mean temperatures decreased and evenness of precipitation around the sidedress N timing increased (Figures 5a–f). Plant N uptake at R6 from the single-N and 45+SD split-N application were generally similar at sites with approximately 49% silt, 27% sand, 19 cmol$_c$ kg^{-1} CEC, 2.1 g kg^{-1} total N, 11:1 C:N ratio, 19–21 ˚C mean temperature between planting and R6, or 0.63 SDI from 30 d before to 15 d after sidedress (Table 3). Additionally, plant N uptake at R6 from the single-N and 90+SD split-N application were generally similar at sites with approximately 67% silt, 6% sand, 30 cmol$_c$ kg^{-1} CEC, 2.4 g kg^{-1} total N, 9.1–13:1 C:N ratio, 18–23 ˚C mean temperature between planting and R6, or 0.57 SDI from 30 d before to 15 d after sidedress. These were the critical values where 1) above these threshold values, plant N uptake at R6 from single-N applications tended to be greater than split-N applications, or 2) below these threshold values, plant N uptake at R6 from split-N applications tended to be greater than single-N applications as stated earlier. The relationships between plant N uptake at VT and R6 from each N application timing treatment and soil parameters and weather conditions (Figure 5a–f; Table 3) were significant ($P \leq .05$) but not strong ($R^2 \leq 0.14$ and $R^2 \leq 0.27$ for plant N uptake at VT and R6, respectively). However, similar to soil NO_3–N, these relationships are important because they helped explain in part how soil and weather conditions influenced the effect of N application timing on plant N uptake at VT and R6.

3.3 | Grain yield

Splitting the N application compared to a single-N application changed grain yield ≤15% of the time (Figure 2b; Supplemental Table S2). Grain yield with single-N application was greater than the 45+SD split 6% of the time and greater than the 90+SD split 1% of the time (0.8 to 2.4 Mg ha^{-1} more with a mean of 1.6 Mg ha^{-1}). On the other hand, grain yield with single-N application was less than the 45+SD split 14% of the time and less than the 90+SD split 15% of the time (1.2 to 4.6 Mg ha^{-1} less with a mean of 2.6 Mg ha^{-1}). Increasing the total N rate from 180 to 270 kg N ha^{-1} rarely changed the effect of N timing on grain yield. In the three site-years where N rate affected N timing, increasing the total N rate had a variable affect. In one site-year, grain yield of the single-N application increased to be similar to the two split applications while in the other two site-years, one or both split-N applications increased grain yield to be similar to the single-N application.

TABLE 4 Critical soil or weather values above which greater grain yield was observed for a single-N application (A) or split-N applications (B). Only soil or weather variables that had a significant interaction with N application timing are shown ($P \leq .05$)

Variable[a]	Critical value 45+SD[b] vs Single	90+SD[c] vs Single	F-value
(A)			
Clay, %	34	37	6.0
Silt, %	66	74	5.1
CEC, $cmol_c\ kg^{-1}$	27	31	7.2
Total N, $g\ kg^{-1}$	2.1	2.4	3.2
Mean temp. (PL–V5), ˚C	19	20	4.7
(B)			
Sand, %	10	4	9.6
Bulk density, $g\ cm^{-3}$	1.2	1.2	3.4
SDI (± 30 d of SD)	0.59	0.56	5.3
SDI (PL–SD)	0.58	0.54	6.3

[a]CEC, Cation exchange capacity; PL, planting; V5, 5-leaf vegetative development stage of corn; SD, sidedress.
[b]45 kg N ha^{-1} at planting and remaining at ∼V9.
[c]90 kg N ha^{-1} at planting and remainder at ∼V9.

Soil and weather conditions did, however, influence the effect of N timing on grain yield (Figure 1; Table 4)

In general, grain yield from the single-N and 45+SD split-N application were generally similar at sites with approximately 34% clay, 66% silt, 10% sand, 27 $cmol_c\ kg^{-1}$ CEC, 2.1 g kg^{-1} total N, or 1.2 g cm^{-3} bulk density (Table 4). Additionally, grain yield from the single-N and 90+SD split-N application were generally similar at sites with approximately 37% clay, 74% silt, 4% sand, 31 $cmol_c\ kg^{-1}$ CEC, 2.4 g kg^{-1} total N, or 1.2 g cm^{-3} bulk density. Grain yield tended to be greater for single- compared to split-N applications when soil parameters were above their critical value for clay, silt, CEC, or total N, or below their critical value for sand or bulk density (Table 4). Single-N application likely had greater grain yield compared to split-N applications in these soils because of their larger soil water and nutrient holding capacity compared to coarse-textured soils with a low CEC (Gehl et al., 2006; Hudson, 1994; Liang & MacKenzie, 1994). These soil conditions reduce the risk of N loss from an at-planting single-N application during the high precipitation and low corn N uptake period that is typical during the early portion of the growing season (Abendroth, Elmore, Boyer, & Marlay, 2011; Dinnes et al., 2002). In contrast, when the opposite was true (greater sand content and lower CEC, total N, and clay and silt content), grain yield tended to be greater for split- compared to single-N application. Split-N applications likely had greater grain yield compared to single-N application in these soils because of their greater potential for N loss during the early part of the growing season as others have reported (Gehl et al., 2005; Nyiraneza et al., 2010; Rasse et al., 1999; Tremblay et al., 2012). Thus, soil parameters can be used to determine whether N fertilizer should be single- or split-applied. Spackman et al. (2019) also arrived at a similar conclusion.

Temperature and precipitation patterns also influenced the effect of single- and split-N applications on grain yield (Table 4). Generally, grain yield from the single-N and 45+SD split-N application were similar with 19 ˚C mean temperatures between planting and V5 corn development or 0.58–0.59 SDI 30 d before and after sidedress application or from planting to sidedress (Table 4). Additionally, grain yield from the single-N and 90+SD split-N application were generally similar with 21 ˚C mean temperatures between planting and V5 corn development or 0.59 and 0.56 SDI 30 d before and after sidedress application or from planting to sidedress.

Grain yield tended to be greater for single- compared to split-N applications when the mean temperature from planting to V5 was above their critical values (Table 4). The same was true when the SDI 30 d before and after sidedress application or from planting to sidedress was below their critical values. Therefore a single-N application is a better option than split-N application to optimize grain yield when greater temperatures from planting to V5 typically occur (mean temperature > 18–23 ˚C) and precipitation is not typically uniform before and after the potential sidedress timing (SDI < 0.54–0.63). Conversely, grain yield from split- relative to single-N applications tended to be greater under the opposite conditions. Therefore split-N applications is a better option than a single-N application when mean temperatures between planting and V5 are typically lower (mean temperature < 18–23 ˚C) and there is uniform precipitation before and after the sidedress application (SDI > 0.54–0.63) or irrigation is available. We suspect that precipitation at the time of sidedress application is important to incorporate the fertilizer into the root zone. Others have observed similar findings (Gehl et al., 2005; Gerwing, Caldwell, & Goodroad, 1979; Jaynes, 2013; Rasse et al., 1999). The strength of the relationships between grain yield from each N application treatment and soil and weather conditions were significant ($P \leq 0.05$) but not strong ($R^2 \leq 0.27$). However, as with other variables already discussed, these relationships are important to help at least partially explain how soil and weather conditions influenced the effect of N application timing on grain yield.

4 | CONCLUSIONS

Across the U.S. Midwest, split applying N relative to a single at-planting application at an optimal or above optimal N rate resulted in similar soil NO_3–N concentration, plant N uptake, and grain yield 65–88% of the time. Since split applications typically require greater logistical planning and additional trips over the field, they provide no real benefit compared to a single at-planting application, except for some important exceptions. The exceptions are soils with high N loss potential early in the growing season, such as coarse-textured soils where the split-N application will result in improved N recovery and grain yield and areas that are likely to have uniform precipitation before and after sidedress application to incorporate the fertilizer into the root zone. Additionally, split-N applications may be used instead of a single-N application without normally reducing corn yield in years where fields cannot be fertilized prior to planting due to wetness or where there are fertilizer shortages in the early spring, potential for lower fertilizer costs later in the season, or a desire to spread out labor requirements. If split applications are used, then a small amount of N at planting (45 or 90 kg ha^{-1}) is adequate to supply crop needs until sidedress without negatively affecting plant N uptake or grain yield.

The effectiveness of split- relative to single-N applications in improving N recovery and reducing N loss is often determined by the level of NO_3–N in the soil after harvest. Soil NO_3–N after harvest was only minimally affected by N timing (≤35% of the time) and that affect only changed in 3 of the 49 site-years when increasing the total N rate to an above optimal rate. The soil NO_3–N content after harvest was influenced more by the precipitation amount and timing before and after sidedress than N recovery by the plant. Therefore, the effectiveness of different N application timings would be better determined by N uptake of the crop, grain yield, or other methods, and not simply by post-harvest soil NO_3–N. Overall, decisions on N application timing to improve soil NO_3–N levels, plant N uptake, and grain yield need to be based on soil parameters and typical weather conditions around the sidedress timing, and except for specific situations, split-N applications are not superior to a single-N application.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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